Perspectives in hadron spectroscopy

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Abstract

A brief survey is presented of selected recent results in hadron spectroscopy and related theoretical studies. This includes the pentaquarks and hadrons containing one or two charmed quarks or antiquarks.

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1 Introduction

In recent months, several new results on hadron physics came from a variety of facilities. Some experiments are not primarily devoted to spectroscopy, but thanks to excellent particle identification and analysis devices, they can perform very well in this field. The tentative discovery of pentaquark states was perhaps the most known of the new findings, but the new excited states of mesons with open or hidden charm, and the new baryons with charm $C = 1$ and $C = 2$ are also of importance.

2 Some new results

Several experimental groups have demonstrated at this Conference the physics potential of their detectors and shown some of their results. This includes, in particular:

- low-lying excitations of D_s mesons, the so-called $D^*_{s,J}$ mesons,
- long-awaited missing states of charmonium,
- new states near 4 GeV/c^2 in the charmonium spectrum,
- confirmation and extension of our knowledge of the spectrum of singly-charmed baryons,
- evidence for doubly-charmed baryons, not yet confirmed by other experiments,
- controversial evidence for the exotic baryons with strangeness or anticharm.

The new findings are not always due to a brute-force increase of statistics, but to the use of new decay channels or new production mechanisms. For example, the radial (${\eta_c}'$) and orbital (h_c) excitations in the spin-singlet sector or charmonium were searched for, and discovered using double-charm production in e^+e^- collisions and weak decay of B mesons, instead of the transition from the higher charmonium states. This ends the charmonium-singlet saga [1], and opens new perspectives. For instance, the double-charm mechanism responsible for the η'_c detection at Belle, as recoiling against the J/ψ, might in future lead to study double-charm baryons and (exotic) the double-charm mesons.

Among the new hadron states, some of them are good candidates for exotic structures: chiral partners of ground-states, hybrid mesons (quark, antiquark and constituent gluon), four-quark states, or meson–meson molecules. We shall briefly review each of these sectors.

3 Understanding new hadrons

3.1 Hybrids

Rather early in the quark model of meson spectroscopy, speculations have been made on new type of excitations, beyond the conventional orbital and radial excitations of a non-relativistic two-body system in a potential [2]. The spectrum and properties of hybrids have been refined, and advertised, from the studies made in the framework of the flux tube model or lattice QCD. A remarkable property is that the hybrids, denoted $(q\bar{q}g)$, do not decay easily into two ground-state mesons, as one of them is preferably an orbital excitation.

Within the adiabatic bag model and also in lattice QCD, the ordinary quarkonium potential corresponds to the slow motion of a heavy $Q\overline{Q}$ pair, with the gluon field remaining in its state of the lowest energy. If the gluon field is excited, another Born–Opppenheimer potential is generated, with a new sequence of bound states. This is very similar to the spectroscopy of $\mathrm{H_2}^+$ in atomic physics, with the ground state and a first sequence of excitations in which the electron is in its lowest orbital, and other sequences, where the electron lies in an excited level.

In the paper revealing the $X(3940)$ [3], the Belle collaboration mentions its possible hybrid nature. Maiani et al. [4], Close et al. [5], and Kou et al. [6], among many others, have recently analysed the latest results in the hidden-charm sector, and arrive to somewhat different conclusions as to which of the new sates is more likely an hybrid, a four-quark state, or a mere $(c\bar{c})$ excitation.

3.2 Diquark models

It is extremely probable that the hadron spectrum can be understood, at least in first approximation, in terms of a few effective entities, in the same way as chemistry use atoms and ions as ingredients whose inner structure rarely matters. The constituent quark model is an illustration, with strongly interacting and massless quarks and gluons making dressed constituent quarks, which in turn build the spectrum of light hadrons. A further simplification consists of assuming that somehow two quarks made a diquark and that baryons are in first approximation made of a quark and a diquark.

The diquark model has been used, perhaps too speculatively, to predict the diquark–antidiquark states, with orbital excitation, as a model of baryonium. When the baryonium disappeared from the tables, the diquark model was looked at with scepticism. It was, however, resurrected with new argumentation, by Jaffe and Wylceck [7], who saw in the diquark model a possible solution to the problem of scalar mesons and of pentaquarks. In this approach, the light pentaquark $\theta^+(1540)$ is essentially an $\bar{s}$ antiquark surrounded by two (ud) diquarks in a relative $\ell = 1$ state of orbital momentum. Karliner and Lipkin [8] further assumed a $(\bar{s}ud)$ type of triquark clustering with a relatively low mass. Maiani et al. [4] explain the $X(3872)$ [9] and $X(3940)$ [3] as a $(c\bar{q}) - (\bar{c}q)$ structures, and that of $Y(4260)$ [10] as $(c\bar{s}) - (\bar{c}s)$.

It should be understood that these sub-structures are effective degrees of freedom in a given context, and cannot be frozen for ever. Otherwise, one would open a Pandora box containing too many new exotic states. For instance, a light triquark $(\bar{s}ud)$, extrapolated naively from the pentaquark, would predict a bound deuteron–$\overline{\Omega}^+$ with baryon number $B = 1$ and strangeness $S = 3$. Similarly, a low mass (cs) diquark [4] could suggest the possibility of a bound dibaryon with charm $C = 3$ and strangeness $S = -3$ below the threshold $(ccc) + (sss)$. Already in 1972, Frederiksson and Jändel [11] mentioned that the diquark model could lead to a "demon-deuteron" state $(ud)^3$. Though their paper has an erroneous statement about the quantum numbers of a three-boson system with an antisymmetric colour wave function, their warning remains.[3]

3.3 Molecules

It is regularly rediscovered that the Yukawa mechanism of nuclear forces is by no means restricted to the two-nucleon systems and presumably holds for any pair of hadrons containing light quarks. Already Fermi and Yang noticed the possibility of a strong attraction between a nucleon and an antinucleon, leading Shapiro, Dover and others to speculate about quasi-nuclear bound states as another approach to baryonium [12].

More recently, several authors noticed the presence of attractive forces in some partial waves of the $D\overline{D}^* + \text{c.c}$ and DD^* systems, mainly due to pion exchange. The potential is weaker than for proton–neutron, but is experienced by heavier particles, and can give rise to binding. The former system, $D\overline{D}^* + \text{c.c}$, is perhaps seen in the $X(3872)$ [9], which is just at the threshold [13]. The latter, DD^*, would correspond to an exotic meson [14] of charm $C = 2$, and is also predicted in pure quark-model calculations, due to the flavour independence of confining forces, which favours $(QQ\bar{q}\bar{q})$ with respect to $(Q\bar{q}) + (Q\bar{q})$ if the mass ratio $m(Q)/m(q)$ is large enough [15].

The case of baryons has been considered by Julia-Diaz and Riska [16] who found the possibility of bound states of charmed or multicharmed baryons. For instance, two of the double charmed baryons [17] presented at this Conference by J. Russ might form a $[(ccq) - (ccq)]$ state stable against spontaneous dissociation, but perhaps above the lower threshold $(ccc) + (cqq)$. This means that an entire new domain of nuclear physics awaits discovery, since, "nuclei" made of several charmed baryons can be envisaged.

In these calculations, one often ends with a two-hadron interaction which is marginally attractive enough to achieve two-body binding, depending on uncontrollable details of the model. Here, the phenomenon of Borromean binding comes to the rescue. Three-body bound states can exists whose two-body subsystems are unstable against dissociation [18].

3.4 Chiral dynamics

Chiral dynamics offers a rigorous and self-consistent framework to study phenomenologically light-quark physics at low energy. The successes are remarkable.

An analysis of the underlying symmetry patterns led to interesting results for hadron spectroscopy, with the possibility of low-lying scalar states, seen as partners of the ground-state pseudoscalars, and to a restoration of parity doublets for highly-excited states. The most dramatic prediction is that of an antidecuplet of light baryons above the known octet (N, Λ, …) and decuplet (Δ, …, Ω^-). The $\theta^+(1540)$ and $\Xi^-(1870)$ are natural candidates for the exotic sector of this $\overline{10}$ multiplet [19]. Unfortunately, the $\theta^+(1540)$ is not seen in most of the high-energy experiments with excellent particle identification and acknowledged record in spectroscopy, as well as in recent measurements at Jlab, where

[3] A correspondance with H.J. Lipkin on this subjet is gratefully acknowledged.

earlier experiments gave positive results. The Ξ^{--} was claimed only by a fraction of a single collaboration, and never confirmed elsewhere and hence its evidence is even weaker. For a recent review of the situation on pentquarks, see, e.g., Kabana [20].

3.5 Chromomagnetism

The chromomagnetic interaction

$$H_{\mathrm{cm}} = -\sum_{i<j} C_{ij} \tilde{\lambda}^c_i . \tilde{\lambda}^c_j \, \boldsymbol{\sigma}_i . \boldsymbol{\sigma_j} \ . \tag{1}$$

though challenged by models based on instanton-induced interaction, or by spin–flavour dynamics, offers a convincing explanation of the hyperfine splittings of ordinary hadrons [21]. Thus Hamiltonian, was very instrumental in demonstrating the possibility of low-lying $(q^2\bar{q}^2)$ states, to explain the presence of supernumerary scalar states of low mass, and in exhibiting the occurrence of coherent attractive forces in selected spin-flavour multiquark configurations.

The chromomagnetic model has been extensively studied, but it can still reveal some suprises for exotic configurations, provided flavour-symmetry breaking is properly accounted for [22].

4 Outlook

A net revival of interest has been observed in the domain of spectroscopy. This takes now a larger fraction of the analysis effort in multipurpose experiments with big detectors at major collider facilities. Estimates of multiquark masses is not restricted to potential models using somewhat ad-hoc colour dependence for the interquark forces. Lattice QCD and QCD sum rules, for instance, are now used to make predictions as a non-trivial extension of the previous works on ordinary mesons and baryons.

It is hoped that this activity will survive the fashion for the pentaquark. New sectors remain to be scanned, in particular those mixing heavy quarks and light quarks, beyond the most accessible hidden charm sector, and this involves intensive analysis.

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